Applications of Formal Verification

Functional Verification of Java Programs: Java Modeling Language

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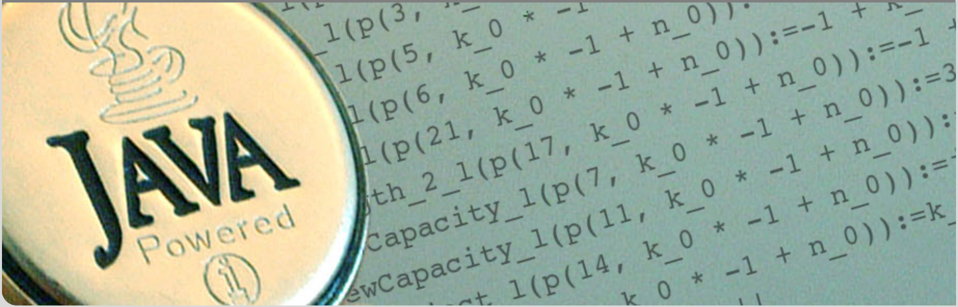

“BISL”

short for

Behavioural Interface Specification Language

- used to describe formally input/output-behaviour of operations
- abstraction from implementation details
  - code structure, algorithms and
  - data structures
- tailored for a particular programming language

Example BISLs:

Java Modeling Language	for	Java
Spec$^{\#}$	for	C$^{\#}$
ACSL	for	C (tool: Frama-C)
VCC	for	C (concurrency)
LARCH/C/C++	for	C/C++ (discontinued)
JAZZ	for	Java (discontinued)

Design by Contract

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Idea

Specifications fix a contract between caller and callee of a method (between client and implementor of a module):

If caller guarantees precondition
then callee guarantees certain outcome

- Interface documentation:
  "Behavioural Interface Specification Language"
- Contracts described in a mathematically precise language (JML)
  - higher degree of precision
  - *automation* of program analysis of various kinds (runtime assertion checking, static verification)
- Note: Errors in specifications are at least as common as errors in code,

JML Annotations


```
/*@ public normal_behavior
  @   requires pin == correctPin;
  @   ensures customerAuthenticated;
  @*/
public void enterPIN (int pin) {
    ...

/*@ public normal_behavior                  //<hello!<
  @   requires pin == correctPin;
  @   ensures customerAuthenticated;
  @*/
public void enterPIN (int pin) {
    ...
```

- Java comments with '@' as first character are JML specifications
- Within a JML annotation, an '@' is ignored:

Visibility Modifiers

```
public class ATM {
  private /*@ spec_public @*/ BankCard insertedCard = null;
  private /*@ spec_public @*/
          boolean  customerAuthenticated = false;

  /*@ public normal_behavior ... @*/
```

- Modifiers to specification cases have no influence on their semantics.
- *public* specification items cannot refer to *private* fields.
- Private fields can be declared public for specification purposes only.

Method Contracts

```
/*@ requires r;
  @ assignable a;
  @ diverges d;
  @ ensures post;
  @ signals_only E1,...,En;
  @ signals(E e) s;
  @*/
T m(...);
```

```
/*@ requires r;        //what is the caller's obligation?
  @ assignable a;
  @ diverges d;
  @ ensures post;
```

Class Invariants

```
//@ invariant i;
```

- can be placed anywhere in a class (or interface)
- express global consistency properties (not specific to a particular method)
- must hold “always”
  (cf. *visible state semantics*, *observed state semantics*, *ownership, dynamic frames*)
- **`instance`** invariants *can*, **`static`** invariants *cannot* refer to **`this`**
- default: **`instance`** within classes, **`static`** within interfaces

Pure Methods

Pure methods terminate and have no side effects.

Hence, they can be used in JML specifications.

After declaring

```
public /*@ pure @*/ boolean cardIsInserted() {
  return insertedCard != null;
}
```

`cardIsInserted()`

could replace

`insertedCard != null`

in JML annotations.

Pure Methods

'`pure`' $\approx$ '`diverges false;`' + '`assignable \nothing;`'

Expressions

- All Java expressions without side-effects
- `==>`, `<==>`: implication, equivalence
- **`\forall`**, **`\exists`**
- **`\num_of`**, **`\sum`**, **`\product`**, **`\min`**, **`\max`**
- **`\old`**(...): referring to pre-state in postconditions
- **`\result`**: referring to return value in postconditions

Quantification in JML

```
(\forall int i; 0<=i && i<\result.length; \result[i]>0)
```
equivalent to
```
(\forall int i; 0<=i && i<\result.length ==> \result[i]>0)
```

```
(\exists int i; 0<=i && i<\result.length; \result[i]>0)
```
equivalent to
```
(\exists int i; 0<=i && i<\result.length && \result[i]>0)
```

- Note that quantifiers bind two expressions, the range predicate and the body expression.
- A missing range predicate is by default `true`.
- JML excludes `null` from the range of quantification.

Generalised and Numerical Quantifiers

`(\num_of T i; e)`	$\#\{i \| [e]\}$, number of elements of type `T` with property `e`
`(\sum T i; p; t)`	$\sum_{i:[p]} [t]$
`(\product T i; p; t)`	$\prod_{i:[p]} [t]$
`(\min T i; p; t)`	$\mathit{min}_{i:[p]}\{[t]\}$
`(\max T i; p; t)`	$\mathit{max}_{i:[p]}\{[t]\}$

The `assignable` Clauses

Comma-separated list of:

- `e.f` (where `f` a field)
- `a[*]`, `a[x..y]` (where `a` an array expression)
- `\nothing`, `\everything` (default)

Example

```
C x, y; int i;
//@ assignable x, x.i;
void m() {
  C tmp = x;   //allowed (local variable)
  tmp.i = 27; //allowed (in assignable clause)
  x = y;       //allowed (in assignable clause)
  x.i = 27;    //forbidden (not local, not in assignable)
}
```

"Nothing" is more than you think it is

`assignable \nothing` means that no memory location **existing at method invocation** must be changed.

Valid specification

```
//@ assignable \nothing;
void n() {
  C c = new C();
  c.i = 42;
}
```

```
//@ assignable \nothing;
void n() {
  C c = new C();
  c.i = 42;    // allowed: fresh objects can be modified
```

The `diverges` Clause

```
diverges e;
```

with a boolean JML expression `e` specifies that the method may may not terminate only when `e` is true in the pre-state.

Examples

```
diverges false;
```

The method must always terminate.

```
diverges true;
```

The method may terminate or not.

```
diverges n == 0;
```

The method must terminate, when called in a state with `n!=0`.

The `signals` Clauses

```
ensures p;
signals_only ET1, ..., ETm;
signals (E1 e1) s1;
...
signals (En en) sn;
```

- normal termination $\Rightarrow$ `p` must hold (in post-state)
- exception thrown $\Rightarrow$ must be of type `ET1`, ..., or `ETm`
- exception of type `E1` thrown $\Rightarrow$ `s1` must hold (in post-state)

  ...
- exception of type `En` thrown $\Rightarrow$ `sn` must hold (in post-state)

Model Fields

```
public interface IBonusCard {

  public void addBonus(int newBonusPoints);

}
```

```
public interface IBonusCard {

/*@ public instance model int bonusPoints; @*/
```

Implementing Interfaces

```
public interface IBonusCard {
   /*@ public instance model int bonusPoints; @*/

   /*@ ... @*/
   public void addBonus(int newBonusPoints);

```

Implementation

```
public class BankCard implements IBonusCard{
     public int bankCardPoints;
/*@  private represents bonusPoints = bankCardPoints; @*/

     public void addBonus(int newBonusPoints) {
       bankCardPoints += newBonusPoints; }
}
```

Other Representations

```
/*@ private represents bonusPoints
            = bankCardPoints; @*/
```

```
/*@ private represents bonusPoints
            = bankCardPoints * 100; @*/
```

```
/*@ represents x \such_that A(x); @*/
```

Inheritance of Specifications in JML

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Behavioral Subtyping, (Lizkov-Leavens Substitution Principle)

If D is a subclass of C, then objects of type C may be replaced with objects of type D without altering the desirable properties of the program.

- A class invariant is inherited by all subclasses.
- An operation contract is inherited by all overridden methods.
- Subclass may add invariants and contracts

Auxiliary Annotations

Dealing with loops

- Loops are a challenge for reasoning about programs
- Loop specifications to guide program proof systems

```
/*@ loop_invariant linv;
  @ decreases variant;
  @ assignable A;
  @*/
while(...) { ... }
```

- Loop invariant *linv* needs to hold for all iterations
  (every time the loop condition is checked)
- The *variant* must be decreasing non-negative integer
  (termination – there is no infinite decreasing sequence)
- assignable, *cf.* `assignable` for methods

Other JML Features

- assertions '`//@ assert e;`'
- assumptions '`//@ assume e;`'
- data groups
- **refines**
- many more...

Nullity

JML has modifiers **`non_null`** and **`nullable`**

```
private /*@spec_public non_null@*/ Object x;
```

⇝ implicit invariant added to class: '**invariant** x != **null;**'

```
void m(/*@non_null@*/ Object p);
```

⇝ implicit precondition added to all contracts:
'**requires** p != **null;**'

```
/*@non_null@*/ Object m();
```

⇝ implicit postcondition added to all contracts:
'**ensures** **result** != **null;**'

`non_null` is the default!
If something may be `null`, you have to declare it **`nullable`**

Problems with Specifications Using Integers

```
/*@ requires y >= 0;
  @ ensures \result >= 0;
  @ ensures \result * \result <= y;
  @ ensures (\result+1) * (\result+1) > y;
  @ */
 public static int isqrt(int y)
```

For $y = 1$ and $\backslash result = 1073741821 = \frac{1}{2}(MAX\_INT - 5)$ the above postcondition is true, though we do not want 1073741821 to be a square root of 1.
JML uses the Java semantics of integers:

$$\begin{aligned} 1073741821 * 1073741821 &= -2147483639 \\ 1073741822 * 1073741822 &= 4 \end{aligned}$$

The JML type `\bigint` provides arbitrary precision integers.

JML Tools

Many tools support JML (see JML homepage). Among them:

- KeY: full static verification
- `OpenJML`: tool suite, under development
- `jml`: JML syntax checker
- `jmldoc`: code documentation (like Javadoc)
- `jmlunit`: unit testing (like JUnit)
- `JMLUnitNG`: unit test generation
- ESC/Java2: leightweight static verification

Many tools do not yet support the new features of Java 5!
e.g.: no generics, no enums, no enhanced for-loops, no autoboxing